

# Dual-microcavity narrow-linewidth Brillouin laser: supplementary material

WILLIAM LOH,<sup>1,\*</sup> ADAM A. S. GREEN,<sup>1</sup> FRED N. BAYNES,<sup>1</sup> DANIEL C. COLE,<sup>1</sup>  
FRANKLYN J. QUINLAN,<sup>1</sup> HANSUEK LEE,<sup>2</sup> KERRY J. VAHALA,<sup>2</sup> SCOTT B. PAPP,<sup>1</sup>  
SCOTT A. DIDDAMS,<sup>1</sup>

<sup>1</sup>Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO, 80305, USA

<sup>2</sup>T. J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA, 91125, USA

\*Corresponding author: [william.loh@nist.gov](mailto:william.loh@nist.gov)

Published 5 March 2015

This document provides supplementary information for “Dual-microcavity narrow-linewidth Brillouin laser,” <http://dx.doi.org/10.1364/optica.2.000225>. In it, we describe the processes by which additional noise couples into the microcavity Brillouin laser. We show that in particular, pump fluctuations result in the introduction of both amplitude and frequency noise beyond the intrinsic noise limits set by Brillouin amplification. We finally show that by stabilizing the pump laser to the cavity resonance, the effects of this pump-noise transfer are significantly reduced. © 2015 Optical Society of America  
<http://dx.doi.org/10.1364/optica.2.000225.s001>

## 1. Microcavity Brillouin Laser Noise Analysis

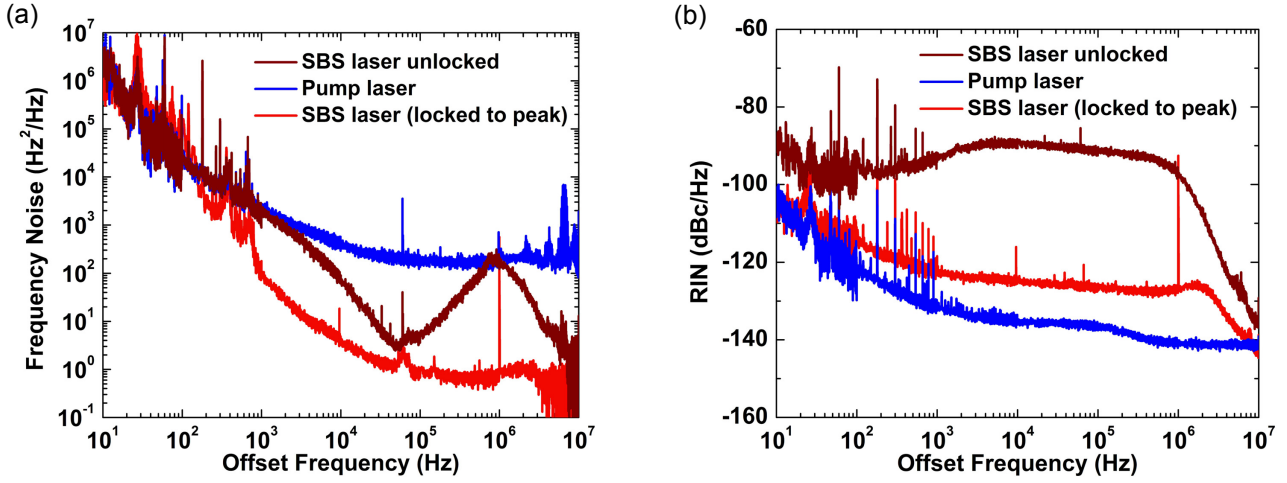
The large ratios of signal to noise in stimulated Brillouin scattering (SBS) microcavity lasers [1, 2] enable spectral purity beyond that which can be achieved by conventional lasers. Taken together with the laser's small size and low pump-power requirements, the SBS microcavity laser exhibits promise as the next generation technology that can bring the performance of state-of-the-art lasers onto a chip-scale platform. Although the theoretical limits of the SBS laser's intrinsic linewidth are in the range of 1 Hz or below, many challenges need to be overcome before the laser's full potential can be realized. We describe here some of these challenges along with our steps taken to overcome them.

The interaction between the thermal bistability [3] of the resonator and the frequency fluctuations of the pump laser result in additional pathways for noise to couple into the SBS laser [4]. Figure S1(a) shows the measured frequency noise of the SBS laser with its corresponding pump laser unlocked and also detuned from the microdisk cavity resonance. For comparison, we have also provided the measured frequency noise of the pump and locked SBS lasers. In the case of the unlocked SBS laser, we find that the SBS laser noise follows the pump noise at low frequencies up to a frequency of ~1 kHz. However, at higher frequencies the noise of the unlocked SBS laser begins to decrease beyond that of the pump but then increases to a resonance peak near 1 MHz. The tracking of the pump-laser noise at low frequencies results from the coupling between pump frequency and temperature in a

resonator. A fluctuation in the pump frequency causes a shift in the intracavity circulating power, which ultimately causes a change in the resonator temperature through the absorbed optical power. A temperature fluctuation of the resonator then results in a frequency shift of *all* the resonator modes, including the mode used for the generation of the SBS light. In this way, the fluctuations of the pump laser are transferred to fluctuations of the SBS laser frequency. This noise transfer occurs on time scales where the resonator can thermally respond to fluctuations in the pump. For the microdisk system, this means that the SBS frequency can follow the pump fluctuations for frequencies up to ~1 kHz (corresponding to the thermal response rate of the microdisk). From Fig. S1(a), we observe that the pump noise transfer is nearly one-to-one into the SBS laser for frequencies below 1 kHz. However, as expected, the strength of this noise transfer decreases for frequencies past 1 kHz.

At even higher offset frequencies beyond 100 kHz, the noise increases and eventually reaches a resonance near 1 MHz. From simulations, we find this resonance to be due to the coupling between amplitude and phase in a cavity, which results in feedback when one of the parameters becomes perturbed [5]. For the SBS laser, the resonance frequency occurs at 1 MHz which corresponds to the inverse of the photon lifetime in the system.

By locking the SBS pump to the cavity resonance, we simultaneously mitigate the effects of both extraneous noise sources. The thermally-induced transfer of noise into the SBS laser occurs through a shift of the pump frequency relative to the cavity



**Fig. S1.** SBS microcavity laser noise. (a) Measured frequency noise of the pump laser (blue), the SBS laser with the pump locked to the resonance peak (red), and the SBS laser with the pump unlocked and also detuned from the cavity resonance (brown). (b) Corresponding RIN measurements for the same laser configurations.

resonance. By stabilizing the pump to the resonance, the fluctuations of the pump relative to the cavity can be corrected for. Similarly, the coupling between amplitude and phase in a cavity is dependent on the detuning of the pump from the cavity resonance. At the resonance center, both phase and amplitude become decoupled from one another so that small-signal fluctuations in the pump frequency result in nearly zero change in circulating optical power, as one would expect from a Lorentzian cavity lineshape. The measured frequency noise of the SBS laser with its corresponding pump laser locked to the resonance peak is shown in Fig. S1(a). In this case, it is clear that both the thermally-induced transfer of pump noise and also the resonance due to amplitude-phase coupling become strongly suppressed. Note that at low frequencies, the thermal fluctuations of the microdisk still result in a significant increase of the SBS laser noise.

Figure S1(b) shows the measured relative intensity noise (RIN) corresponding to the pump laser and the locked and unlocked SBS lasers. With the pump laser unlocked and detuned from the cavity resonance, the frequency fluctuations of the pump directly result in shifts of the intracavity circulating power and ultimately in the SBS power. This process governs the transfer of the pump frequency noise into the RIN of the SBS laser. At low frequencies below  $\sim 1$  kHz, the thermal response of the cavity modes to intracavity power fluctuations acts to shift the modes in the direction of the pump frequency fluctuation. This phenomenon of thermal locking stabilizes the microresonator against intracavity power fluctuations. As a result, the SBS laser RIN decreases below 1 kHz, which corresponds to the thermal response rate of the system. By locking the pump laser to the resonance peak, the coupling of amplitude and phase is once again significantly reduced. This is evident in the large decrease in RIN for the locked SBS laser.

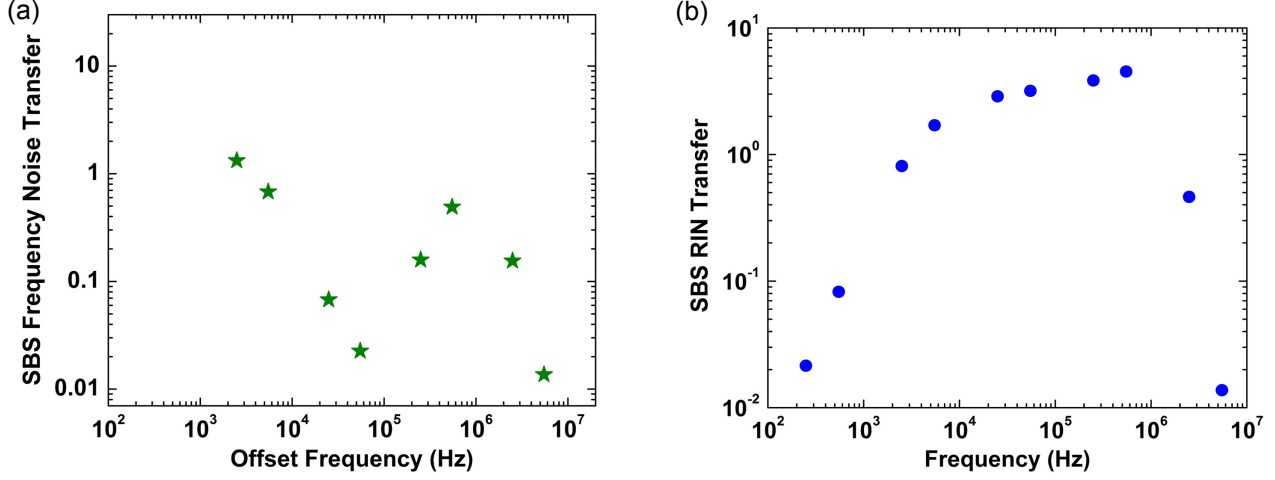
## 2. Microcavity Brillouin Laser Noise Transfer

In the previous section, we described different paths for pump noise to couple into the SBS laser. Here, we investigate this noise transfer further by performing direct measurements of the pump-noise conversion. We perform these measurements through a controlled modulation of either the pump phase/frequency or amplitude. We then measure the frequency noise or RIN of the

resulting response normalized to that of the initial applied modulation. The measurement of frequency noise is carried out using a Mach-Zehnder interferometer comprising varying delay lengths up to 200 m, while the RIN measurement is performed by direct photodetection of the signal. By sweeping the applied modulation across several points in the range of 100 Hz to 10 MHz, we effectively map out the pump-noise transfer spectrally across frequency.

Figure S2(a) shows the conversion of pump frequency noise into SBS frequency noise. This frequency-noise transfer reaches a local minimum of  $\sim 0.02$  near 50 kHz, as one would expect comparing the unlocked SBS noise to the pump noise in Fig. S1(a). We therefore find that 2 % of the pump frequency noise becomes converted into fluctuations of the SBS signal. Although the amount of pump-noise transfer is controlled by the properties of the resonator, the effects of this noise can be diminished by locking the pump to the cavity resonance. Through this stabilization, the pump frequency fluctuations are first reduced before they become subsequently transferred to the SBS signal. At offset frequencies above 50 kHz, the pump-noise transfer increases and eventually reaches a resonance near 1 MHz [compare to Fig. S1(a)]. For offset frequencies below 50 kHz, the thermal response of the microresonator causes the SBS mode to begin to follow the pump frequency fluctuations. This effect drives the noise transfer to unity at low frequencies. These noise contributions are again mitigated by stabilizing the pump to the cavity, as discussed in the previous section. Note that the sensitivity of the frequency noise measurement to amplitude noise combined with the inability to modulate purely on phase/frequency prevents the full characterization of the frequency-noise transfer for offset frequencies below  $\sim 1$  kHz.

Figure S2(b) shows the RIN transfer from the pump into the SBS signal. Near 50 kHz, this RIN transfer reaches a value of  $\sim 3$ , signifying that three times the pump RIN becomes converted over as SBS RIN. At larger offset frequencies, the RIN transfer reaches a damped resonance at 1 MHz before decaying at even higher frequencies. Below 50 kHz, the noise begins to decrease again due to the intrinsic thermal locking of the pump to the cavity resonance. A pump amplitude fluctuation results in heating (or cooling) of the microresonator, which then acts to shift the cavity



**Fig. S2.** Transfer of pump noise into the SBS laser. (a) Measured pump frequency-noise transfer as a function of offset frequency. (b) Measured pump RIN transfer as a function of offset frequency.

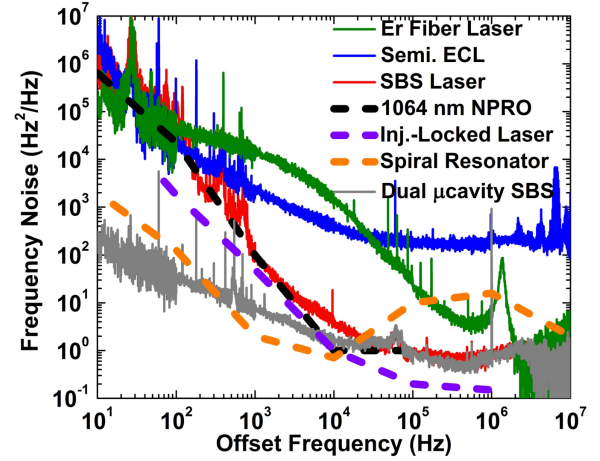
resonance in a direction relative to the pump that counteracts the increase (or decrease) in optical power. In this way, the intracavity circulating power and also the SBS power both become stabilized against pump amplitude fluctuations. We observe the effects of this noise suppression in Fig. 2(b) for frequencies below a few kilohertz. Note that although not shown here, a similar technique can also be applied to measure the cross conversion of pump noise from frequency to amplitude and vice versa.

### 3. Laser Noise Comparison

In the previous sections, we discussed the subtleties regarding how to suppress extraneous noise in the operation of the SBS laser. Here, we compare the performance of the SBS laser to other laser sources available either commercially or in the literature. This comparison serves to both highlight the SBS laser's performance and also to provide appropriate context for the level of noise exhibited by the SBS laser.

Figure S3 shows a plot of the frequency noise comparing the pump and SBS lasers to commercial Er fiber and non-planar ring oscillator (NPRO) lasers and to the advanced injection-locked [6] and spiral resonator [7] lasers reported in literature. The pump semiconductor external-cavity laser (ECL) frequency noise and also the frequency noise of the SBS laser and dual-microcavity SBS laser all follow their measured values provided in the main text. For reference, we note that the pump, SBS, and dual-microcavity SBS lasers exhibited linewidths of 7.9 kHz, 3.3 kHz, and 95 Hz, respectively. In comparison to the pump laser, we observe that the commercial Er fiber laser exhibits slightly higher frequency noise below 30 kHz offset but demonstrates lower noise beyond 30 kHz. However, the noise of the Er fiber laser is clearly larger compared to that of both the SBS and dual-microcavity SBS lasers at all frequencies tested. On the other hand, the performance of the 1064 nm NPRO laser (obtained from Ref. [8]) is comparable to that of the SBS laser. However, compared to the dual-microcavity SBS laser, the NPRO laser frequency noise is four orders of magnitude larger at low offset frequencies ( $\sim 10$  Hz).

The injection-locked laser [6, 9] is a recent class of lasers whose noise performance is achieved through the optical feedback provided by a high-Q whispering-gallery mode resonator. The seed laser is a semiconductor distributed feedback (DFB) laser, and thus the scale of the injection-locked laser is similar to that of



**Fig. S3.** Frequency noise of several laser technologies. The measured frequency noise of the semiconductor ECL (blue solid line), SBS laser (red solid line), and dual microcavity SBS laser (gray solid line) are taken from Fig. 3 of the main text. The frequency noise of the Er fiber laser (green solid line) was separately measured, while the noise of the 1064 nm NPRO laser (black dashed line) was taken from Ref. [8]. Finally, the frequency noise of the injection-locked laser (purple dashed line) and the spiral resonator laser (orange dashed line) were calculated from the phase noise of Refs. [6] and [7], respectively.

the SBS laser. These injection-locked lasers obtain very low noise at high offset frequencies reaching levels of  $0.2 \text{ Hz}^2/\text{Hz}$  at 100 kHz, which is a factor of two-to-three lower than that of the SBS laser exhibited here. With the use of microresonators having larger mode volume, the SBS laser noise can be improved to be below this limit. Furthermore, the noise of the injection-locked lasers degrades at lower frequencies and becomes approximately two orders of magnitude larger than the noise of the dual-microcavity SBS laser at 100 Hz offset.

Finally, the spiral resonator [7] is a recently-demonstrated planar reference cavity where low-noise operation is achieved by locking a laser to a large mode-volume spiral resonator. By coiling

a silica waveguide on a compact silicon chip, resonators  $>1$  m in length with Q-factors  $>10^8$  have been demonstrated. The seed laser used in the data shown here was an Er fiber laser, and thus the system scale is intrinsically larger than that of the SBS laser system. Nevertheless, from Fig. S3, it is clear that over the range of 300 Hz to 20 kHz, the spiral resonator achieves a factor of two-to-three lower noise compared to that of the dual-microcavity SBS laser. However, below 300 Hz and above 20 kHz, the noise increases reaching an order of magnitude higher noise at 10 Hz offset and over an order of magnitude higher beyond 100 kHz. Note that the servo peak of the spiral resonator system was not plotted in Fig. S3 but can be found in the noise spectrum at  $\sim 200$  kHz offset in Ref. [7]. Since the spiral reference cavity is a planar device on silicon, it represents an interesting platform for future integration with the SBS laser or other semiconductor-based lasers.

## References

1. I. S. Grudin, A. B. Matsko, and L. Maleki, "Brillouin lasing with a  $\text{CaF}_2$  whispering gallery mode resonator," *Phys. Rev. Lett.* **102**, 043902 (2009).
2. H. Lee, T. Chen, J. Li, K. Yang, S. Jeon, O. Painter, and K. J. Vahala, "Chemically etched ultrahigh-Q wedge-resonator on a silicon chip," *Nature Photon.* **6**, 369-373 (2012).
3. V. S. Il'chenko and M. L. Gorodetskii, "Thermal nonlinear effects in optical whispering gallery microresonators," *Laser Phys.* **2**, 1004-1009 (1992).
4. J. Li, S. Diddams, and K. J. Vahala, "Pump frequency noise coupling into a microcavity by thermo-optic locking," *Opt. Express* **22**, 14559-14567 (2014).
5. W. Loh, S. B. Papp, and S. A. Diddams, "Noise and dynamics of stimulated Brillouin scattering microresonator lasers," arXiv:1410.8611 (2014).
6. E. Dale, W. Liang, D. Eliyahu, A. A. Savchenkov, V. S. Ilchenko, A. B. Matsko, D. Seidel, and L. Maleki, "On phase noise of self-injection locked semiconductor lasers," *Proc. SPIE* 8960, (2014).
7. H. Lee, M.-G. Suh, T. Chen, J. Li, S. A. Diddams, and K. J. Vahala, "Spiral resonators for on-chip laser frequency stabilization," *Nat. Commun.* **4**, 2468 (2013).
8. K. Numata, J. Camp, M. A. Krainak, and L. Stolpner, "Performance of planar-waveguide external cavity laser for precision measurements," *Opt. Express* **18**, 22781-22788 (2010).
9. W. Liang, V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, D. Seidel, and L. Maleki, "Whispering-gallery-mode resonator-based ultranarrow linewidth external-cavity semiconductor laser," *Opt. Lett.* **35**, 2822-2824 (2010).